The Effect of Rainfall Intensity on Slope Stability: An Analytical Study using Numerical Modeling

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ABSTRACT

Slope instability causes landslides, which have a detrimental effect on infrastructure and the environment while contributing to significant damage both in terms of people and property. The present article offers a thorough examination of slope stability by SEEP/W and SLOPE/W software programs. Using numerical simulations based on three different models, the work plan analyzed changes in moisture content, Pore Water Pressure (PWP), and factor of safety (F.S.) to assess the impact of a set of hydrological and engineering factors, such as rainfall intensity (I), soil permeability (K), and slope angles (S). Based on the results, PWP rises to 185.84 kPa and the F.S. drops to 1.233 as rainfall intensity exceeds 80 mm/h. Additionally, longer rainfall intervals (3 days) result in a 20% reduction in F.S. as compared to short rainfall periods. The study also found that steep slopes (30° or more) greatly enhance the chance of falling apart, particularly in highly permeable soils, while the rapid water seepage along gradients caused by highly permeable soils increases the danger of collapse. The findings suggest that, in addition to enhancing soil qualities in high-permeability areas and utilizing efficient drainage systems to lower pore pressure, engineering projects should consider the impact of heavy rainfall and extended precipitation. Furthermore, a novel mathematical equation was developed to calculate the F.S. of slopes, incorporating key parameters, such as rainfall intensity, slope angle, and soil type. This equation underwent rigorous statistical analysis, achieving the highest accuracy rate, and can serve as a robust tool for slope stability assessment in diverse environmental and engineering scenarios.

Keywords-factor of safety; slope stability; rainfall intensity; SEEP/W; SLOPE/W; pore water pressure

I. INTRODUCTION

Slope stability is a major construction challenge in areas with steep terrain, and it has a direct influence on the safety of projects. Considering the increase in rainfall caused by changes in the climate, the development of human activity in the highlands, and all research results, one of the major factors determining slope stability is the rainfall intensity. According to [1], significant rainfall can raise the soil's pore pressure affecting slope stability. A rainfall threshold of more than eight hours or 45.6 mm cumulative rainfall, meaning a rainfall with 5.7 mm/h intensity, could be used as an early warning system for disaster-prone locations. Authors in [2] demonstrated that the slow buildup of pore pressure in soils with low permeability increases the danger of landslides. High permeability also contributes to rapid moisture penetration, which immediately reduces slope stability. Studies have demonstrated that infiltration causes advanced landslides by raising groundwater pressure and pore water. The slope F.S. was influenced by the permeability values and time length, with severe circumstances developing with three consecutive days of rain. These elements should be taken into account for the slope's stability [3].

The impact of excessive precipitation on slope and soil stability demonstrates that slope failure is caused by a loss of soil suction and positive water pressure at the slope's base. The use of jute fiber into the soil greatly increased its strength and F.S. in a variety of rainfall scenarios, hence boosting soil stability and decreasing the chance of collapse [4]. High-intensity tropical rains significantly decrease the F.S., in some cases up to 50% [5]. The employment of hydrological models in numerical assessments is also crucial, as it might decrease the predicted errors by as much as 20% [6]. According to [7], the F.S. drops to 1.31 when there is long rainfall from 2.13 in dry conditions, highlighting the necessity of enhancing the drainage systems on earthen slopes. Authors in [8] examined the impact of rainfall on slope stability using both numerical modeling and experiments, and found that in highly permeable soils, more rapid landslides result from the decreasing matrix absorption as pore pressure increases. Slope stability is impacted by advanced, delayed, and normal rainfall patterns, with advanced patterns yielding a higher drop in the F.S. than other patterns [9]. The effects of prior rainfall had been investigated in [10] and the results showed that the dual analyses increased forecast accuracy by 25%. In [11], it was reported that pore pressure due to rainwater infiltration causes foundation failure in 65% of the collapse instances in sandy soils. Examining the rainfall-induced hydraulic response of a slope and the mechanism of failure with the installation of bottom filters can increase the F.S. for earth dams by up to 10% [12]. According to [13], using artificial neural network models in conjunction with the Geo-Studio software may estimate the stability of slopes under various flow circumstances with an accuracy of up to 97.8%. To evaluate the effect of rainfall on infrastructure projects, Salah al-Din Governorate, [14] also affirmed the significance of examining Intensity-Duration-Frequency (IDF) curves for designing drainage systems.

Throughout all this effort, many studies tend to disregard the intricate interactions between many parameters, such as slope angle, permeability, and the intensity of precipitation, in preference of investigating instead rainfall intensity and its direct impact on pore pressure and F.S. Furthermore, rapidly changing time-related events and the impact of long-term climatic changes are frequently disregarded by the current numerical models. Therefore, by developing powerful numerical models that completely consider these concerns, the current project attempts to fill in these gaps.

II. NUMERICAL MODEL AND BOUNDARY CONDITIONS

Using the Geo-Studio software, a two-dimensional numerical model was produced. The model was based on a slope that is 10 m high and had slope angles of 30°, 35°, and 40°. The model was divided into a network of 1197 rectangular elements, with 1278 nodes surrounding each division, and an edge size of 1.25, offering accurate numerical distribution and excellent analysis of the stresses and pore pressure in the soil. To prevent any unnecessary leakage that may impact the result accuracy, fixed conditions were given at the bottom and side limits of the boundary conditions, which were systematically designed to replicate the surface and groundwater movement. The initial groundwater level was set at 10 m above the base of the model, as displayed in Figure 1.

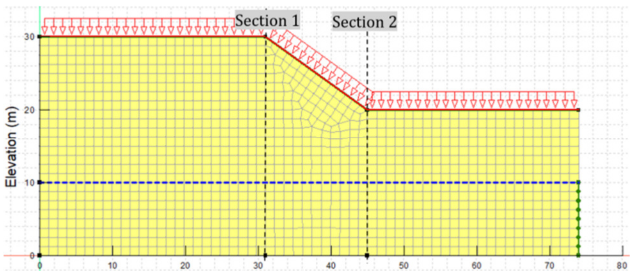

Fig. 1. Numerical model and boundary condition.

The factors that affect the slope stability included rainfall intensity, with values 9, 20, and 80 mm/h representing low medium, and heavy intensity, covering a wide range of hydrological scenarios. Soil permeability, with (low-high) values 10-4, 10-5, and 10-6 m/s, reflecting the effect of different soil properties on slope stability. In addition, the effect of different slope angles was studied to determine the critical angle that increases the probability of collapse, and the rainfall duration of 1, 2, and 3 days, so the number of the prepared tests was 81 scenarios.

The equilibrium of a soil mass enclosed by the slope surface along with a potential slip surface will be studied via a traditional slope stability analysis, contrasting the moments and forces that resist with those that cause the mass to move. The shear forces, PWP on the slip surface, additional forces, like acceleration or dynamic overloads, and mass load all affect stability, while there are additional internal responses to the imagined slip surface. The ratio of real shear resistance to the shear strength needed to reach the soil equilibrium is known as the F.S. and is calculated by [15, 16]:

$$F.S. = \frac{C + (\sigma - U)\tan\theta}{\tau} \qquad (1)$$

where C is the soil cohesion, θ is the internal friction angle, (σ-U) is the stress on the failure plane, and τ is the sum of driving forces.

The entry and exit method is one of the techniques used in slope stability analysis. The aim of this technique is to identify possible slip surfaces by defining various possibilities for slip surfaces to enter and exit from the ground surface. This technique is frequently employed in slope stability analysis software, such as SLOPE/W, where the entry and exit positions are either automatically or manually calculated based on the site's geological and technical features. The ground surface is indicated with the entry and exit lines in Figure 2.

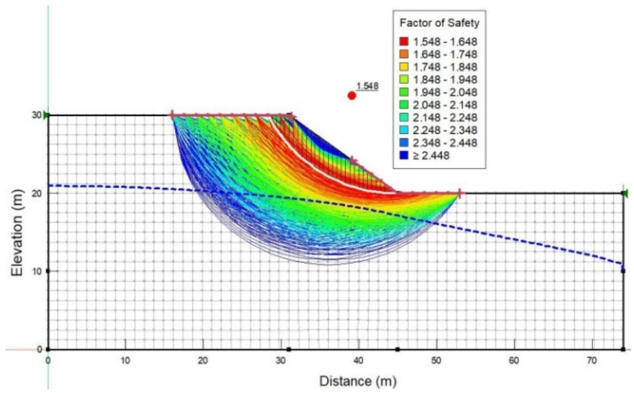

Fig. 2. Numerical model Entry and Exit.

III. HYDROLOGICAL AND STABILITY ANALYSIS

The hydrological analysis, that evaluated the water movement in the soil, was based on the SEEP/W software. Figure 3 illustrates the extent to which the variations in pore pressure were monitored throughout several rainfall events. Figure 4 depicts how the moisture contained within the slope was examined using quantitative modeling methods, enabling a thorough comprehension of the variation in moisture content and its effect on soil stability.

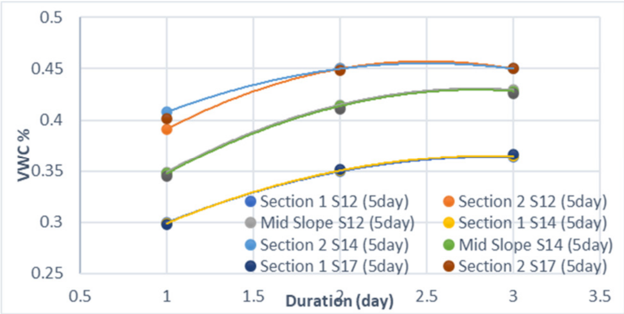

Fig. 3. Volumetric Water Content (VWC) through time.

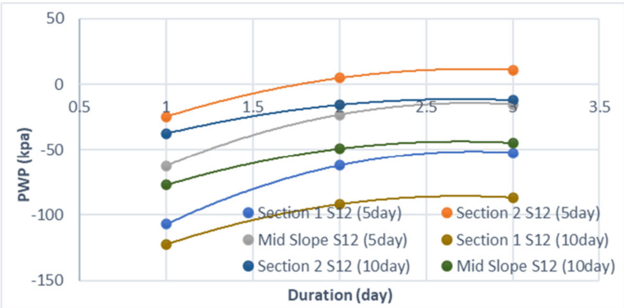

Fig. 4. PWP through time.

IV. EFFECT OF RAINFALL INTENSITY AND PORE WATER PRESSURE

The slope stability was significantly impacted by the rain severity. The results demonstrated that excessive intensity at a rate of 80 mm/h increased the pore pressure to 185.84 kPa, as observed in Figure 5, whereas rainfall at a rate of 9 mm/h produced a comparatively low pore pressure of around 50 kPa. Furthermore, the results demonstrated a roughly linear connection between the rainfall intensity and pore pressure up to a certain limit, with the pore pressure being 123.45 kPa at a rainfall intensity of 40 mm/h. Despite this rise in pore pressure, the F.S. significantly decreased from 1.88 to 1.233, indicating a serious decline in stability as rainfall intensity increased. Thus, the slope stability decreased because of the alteration in pore pressure with varying rainfall intensity.

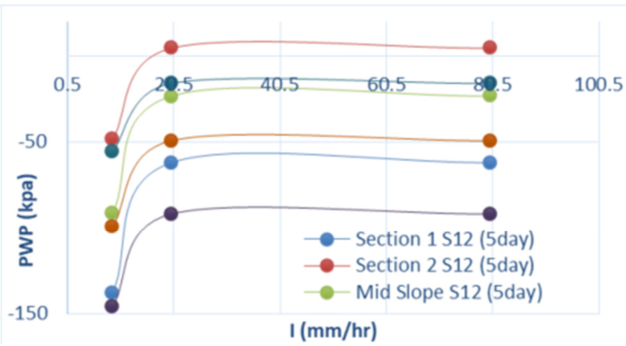

Fig. 5. Effect of rainfall intensity on PWP.

V. IMPACT OF THE SOIL'S PERMEABILITY ON SLOPE STABILITY

Within 30 min of precipitation, the high-permeability soil rapidly saturated, causing the F.S. to drop sharply to 1.45, as portrayed in Figure 6. Conversely, the low-permeability soil held for extended periods of rainfall, which raised the pore pressure gradually over time and eventually reached 95 kPa in just two hours. These findings demonstrate how permeability characteristics affect the dynamic movement of water in soil, because quick seepage in high-permeability soil causes an abrupt drop in stability, whereas low-permeability soil causes water buildup and gradual pressure increases.

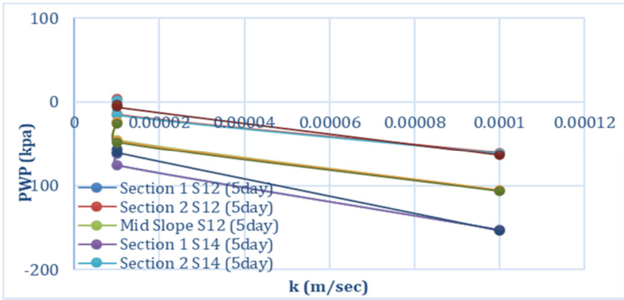

Fig. 6. Effect of permeability on PWP.

VI. PORE WATER PRESSURE DISTRIBUTION

The change in PWP underneath a slope of 30° angle is presented in Figure 7. This occurs along the path from the slope's beginning at Section 1 (distance 0 m) via the Mid-Point to its end at Section 2 (distance 14 m), as can be seen in Figure 1. Owing to the surface tension interactions between the soil particles, the initial pore pressure can be defined by low values, frequently negative, indicating an unsaturated zone with higher shear resistance. The pore pressure starts to progressively build while approaching the middle of the distance because of the increase in saturation brought on by the water's flow under the effect of gravity. At the end of the slope at Section 2 (Figure 1), the values reach their highest levels due to water accumulation and increased saturation, which leads to a decrease in the effective stress of the soil and a weakening of the shear resistance. This shows the importance of the relationship between the distribution of pore pressure and distance on slope stability, where a negative pore pressure at the start is considered an element that enhances stability, while an increase at the end of the slope poses a potential risk of collapse.

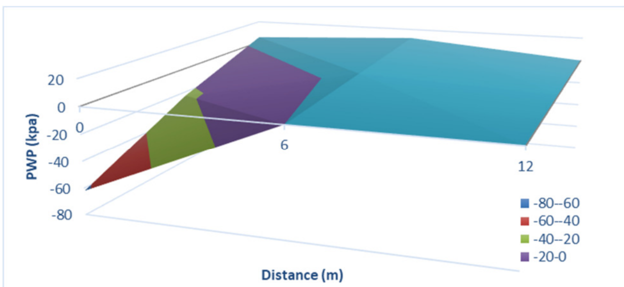

Fig. 7. PWP distribution under slope 30°.

VII. SLOPE ANGLE'S EFFECT ON SLOPE STABILITY

Slope stability was significantly influenced by the slope angle. The findings demonstrated that as the slope angle increased, the F.S. progressively dropped. The F.S. was 1.6 at a slope angle of 30° and dropped to 1.233 at a slope angle of 40°, as evidenced in Figure 8.

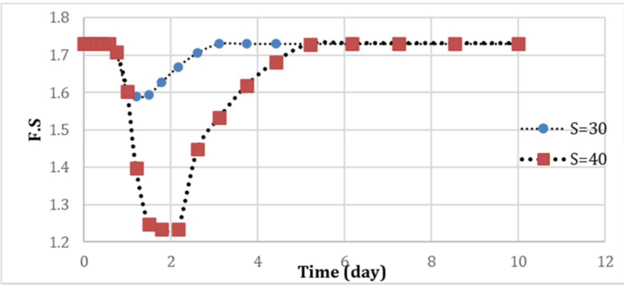

Fig. 8. Slope stability through time.

VIII. EFFECT OF FLOW AND MOISTURE CONTENT

The relationship between pore pressure and moisture content is demonstrated by the flow data in Figure 9, where variations in the moisture content raise the probability of collapse on slopes. Thus, the dynamics of slope stability changed significantly within the first hour as the surface soil's moisture content grew by 35% at a rainfall intensity of 50 mm/h. These results are in line with Terzaghi's theory of effective stress, which holds that a rising pore pressure lowers the soil's effective stress, reducing the shear resistance and raising the possibility of collapse.

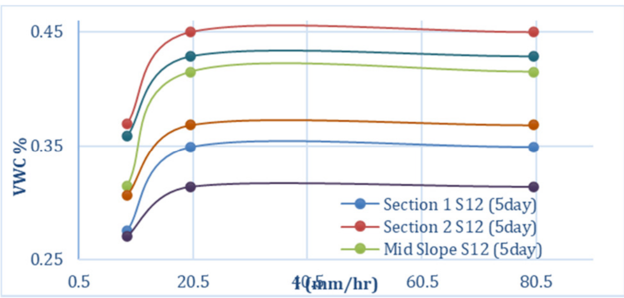

Fig. 9. Effect of rainfall intensity on VWC.

IX. FACTOR OF SAFETY EQUATION

Based on the results and data extracted from the current research, a non-linear equation was developed that allows the calculation of the F.S., taking into account the effect of various relevant variables. This equation is considered an effective tool for researchers and engineers to accurately estimate the levels of slope stability. Equation (2) provides the final formulation of this mathematical relationship:

$$F.S. = 0.28 \cdot I^{-0.054} \cdot k^{-0.003} \cdot d^{-0.085} \cdot S^{0.704} \quad (2)$$

The correlation coefficient shows the degree to which geotechnical characteristics, such as permeability, slope angle, and rainfall intensity, are related to the F.S., whereas the Standard Deviation (SD) shows the diversity in these characteristics. A high correlation value (around 1) indicates a strong connection between the variables under study, highlighting the significance of variability in affecting the slope stability, as depicted in Figure 10. An accurate equation to get the F.S. must consider the nonlinear relationship between these variables.

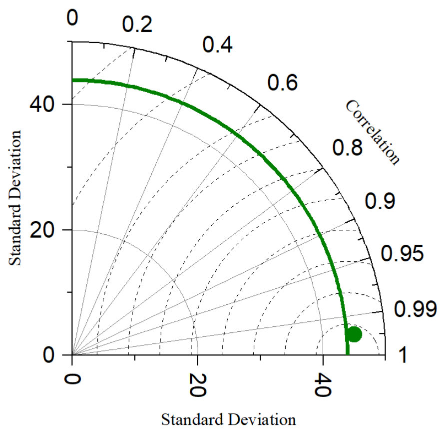

Fig. 10. Taylor diagram for (2).

Figure 11 provides a radar indication for the slope F.S. using (2). To provide a complete and accurate evaluation, the formula was tested with an ensemble of statistical indicators selected based on [17]. These metrics include: R^2, which shows how well the computed and observed values coincide, NSE, which rates how well the model reduces errors, a balance between correlation, variance, and deviation is represented by KGE, the strength of the linear relationship between values is measured by (pcorr), the maximum relative error is obtained by (RE max.), and the performance ratios between the variables are reflected by (Ratio). Once the variables approach high levels close to 1.00, the findings in the Figure 11 exhibit outstanding efficiency, the model's accuracy, as well as consistency in representing the data. This performance demonstrates the viability of the proposed equation in collecting the interaction of the various variables related to the slope F.S., as well as how well it can achieve high level of consistency and accuracy resulting in an effective way for real-world slope stability fields.

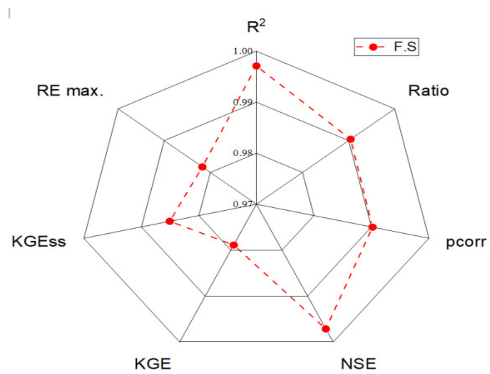

Fig. 11. Radar diagram for (2).

X. CONCLUSIONS

The current research evaluates the slope stability under a variety of situations, including the impacts of rainfall intensity (I), soil permeability (K), slope angle (S), and seasonal variations. The primary findings are:

- Rainfall Intensity: Heavy rainfall with intensity 80 mm/h rapidly decreases the Factor of Safety (F.S.) to 1.233, highlighting the important unstable criteria and the significance of the appropriate drainage systems.
- Soil Permeability: The saturation of highly permeable soils is rapid, resulting in a significant reduction in stability, whereas low-permeability soils collect pore pressure as time passes, adding long-term hazards.
- Slope Angle: Steeper slope angles weaken stability substantially, bringing out the significance of suitable slope designs to avoid severe collapses.
- Seasonal Effects: Hydrological and geotechnical hazards rise with time, especially for soils with limited permeability, indicating the importance of long-term observation.
- Innovative Contribution: By combining soil type, slope angle, and rainfall intensity, an equation has been developed to determine a slope's F.S. This equation is a useful tool for evaluating slope stability in a variety of settings and has been confirmed with good statistical accuracy.

The research shows how the mathematical equation developed may be efficiently relied on to provide quick, initial assessments of the slope stability for several scenarios that include hydrological and geotechnical components, conserving time and effort. It additionally proposes the construction of effective drainage networks, optimizing slope angles, setting up soil stabilization approaches, and assessing pore pressure and moisture content frequently to minimize hazards and the risk of slope failure.

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